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Determination of Strategy for Harvesting Burley Tobacco

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ABSTRACT

THE decision-making process associated with the scheduling of burley tobacco harvesting operations was formulated as a multi-stage decision process, and solved using a procedure called dynamic programming. The solution of a stochastic dynamic programming model provides a set of optimal decision rules, that is, a strategy. When certain user-specified parameters are provided, the decision model provides information concerning the optimal date to start harvesting, the optimal number of hours to harvest on each day, the optimal date to introduce hired labor, and the optimal number of workers which should be hired.

The solution of the dynamic programming model makes it possible to compute a timeliness cost which is defined as the amount of the expected total return which is lost because of delaying harvest initiation beyond the optimal starting day. Thus, a decision-maker can consult tabulated strategy solutions in any situation during the harvesting season and make decisions with the aid of timeliness cost information.

INTRODUCTION

One of the most important decisions in producing high quality burley tobacco is deciding when to harvest, since its value is closely related to the harvesting date (Heggestad and Bowman, 1953). Timely harvesting can be achieved only through a complex decision-making process which must take many factors into account.

A crop value function is illustrated in Fig. 1, which shows that crop value varies with time in a manner similar to a quadratic relationship. The abscissa in Fig. 1 need not be calendar date, but may be the time measured from the occurrence of a biological development of the crop.

Under normal climatic conditions, burley tobacco attains a maximum value at some time, t_0, which is approximately 25 days after topping (Heggestad and Bowman, 1953). Since some time is required to harvest tobacco, a farmer must begin harvesting on some day, t_1, prior to maximum value day, t_0. Harvesting time (t_2 - t_1), called a scheduling time bracket, is a management variable which may depend on harvesting capacity, field size and other factors.

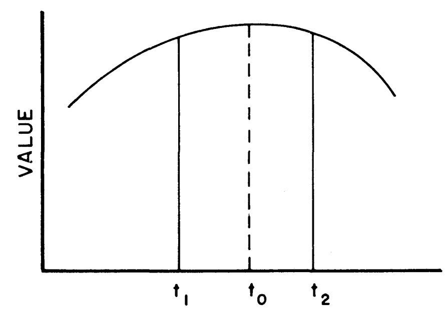

FIG. 1 Conceptual crop value function for burley tobacco near maturity.

Another important factor which makes the farmer's decision-making process more complicated is that of weather. Weather conditions not only influence the growth of burley tobacco, but also directly affect working conditions in the field at this stage. A workable day can be defined by taking into account precipitation, soil moisture and other factors.

Generally, the harvesting season in Kentucky begins in late August and terminates in early October. Therefore, a harvesting schedule must be established by considering the climatic conditions during this period. This uncontrollable factor in the harvesting process can be considered by deriving the probability of workable field conditions for each day during the harvesting season.

Increasing costs associated with harvesting burley tobacco and the importance of timeliness in achieving maximum economic return compel producers to schedule and manage field operations carefully and effectively. It is thus desirable to introduce a systems analysis technique as a managerial tool to be used in scheduling harvesting operations in an optimal manner. The primary goal of this study is to develop a mathematical decision model which provides information concerning:

1 The optimal date to start harvesting and the optimal number of hours to harvest on each day during the harvesting season, and

2 When to introduce the hired labor and how many workers should be hired.

BACKGROUND

Such a complex decision-making process would be difficult to analyze using conventional mathematical programming techniques, but it can be well formulated as a multi-stage decision process and be solved, using a procedure called dynamic programming. In contrast to the normal formulation of an optimization problem where the entire problem is solved as a total entity, the dynamic programming technique determines the optimal

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sequence of decisions in a multi-stage decision process which can be transformed into a series of single-stage decision processes. A stochastic version of the dynamic programming technique provides optimal decision rules, that is, a strategy. The dynamic programming technique was developed by Bellman (1957) and Bellman and Dreyfus (1962).

A dynamic programming algorithm was used by Schroeder and Peart (1967) to investigate the air distribution pattern in a continuous flow column grain drier. A similar approach was used in describing size sorting of agricultural products (Liang, 1969) and for predicting inventory demand for farm machinery replacement parts (Liang and Link, 1970). Agricultural economists have been using the dynamic programming approach to solve replacement problems (Jenkins and Halter, 1963) and to schedule operations to maximize profits (Low and Brookhouse, 1965).

Morey et al. (1971) developed a dynamic programming model for the purpose of determining the optimal decison rules for corn harvesting during a fixed harvesting season. The strategy developed here employs a similar technique, however, emphasis is placed on the determination of the most timely starting date for harvesting and upon the development of optimal decision criteria for the hiring of additional laborers to augment full-time or family laborers.

MODEL FORMULATION

In order to complete the harvesting process in the manner which produces the maximum total return, a farmer must consider not only the expected return for the present period but also the expected return for future periods. More specifically, the decision maker must estimate the expected return for the present period, predict expected returns for future periods in the light of the present state of the system, and finally, make decisions so as to maximize the sum of these expected returns.

In the dynamic programming approach, a process is considered as a series of sequential stages. For convenience of computational notation, stages are numbered backward, that is, in the opposite direction of the process. In this context, the number assigned to each stage indicates the number of stages remaining before termination of the process.

A stage (n) may be characterized by a state variable (s_n). A state variable is one which, being both an input to one stage and an output from another, transmits information about previous stages which is relevant to selecting a current optimal value for a decision variable. A decision variable (d_n) is controllable by a decision-maker and has a forecastable influence on the state at the next stage.

The relationship which expresses the stage return in terms of the inputs at stage n is called the return function, R_n. The transformation relationship having the state variable s_{n-1} as its output is called a transition function and is written as T_n. Once R_n and T_n are defined, a multi-stage decision process can be studied by formulating a recurrent functional equation as follows:

$$f_n(s_n) = \underset{d_n}{\mathrm{Max}} \left[R_n(d_n, s_n) + f_{n-1}(T_n(d_n, s_n)) \right] \quad \ldots\ldots\ldots [1]$$

where the operator $\underset{d_n}{\text{“Max”}}$ refers to the determination of the value of d_n which maximizes the expected total return. Thus, $f_n(s_n)$ expresses the maximum total return from following an optimal policy over n stages beginning in state s_n at stage n.

Equation [1] was formulated under the assumption that a new state s_{n-1} and stage return could be determined uniquely once the previous state s_n and decision d_n are known, and is, therefore, referred to as a deterministic dynamic programming model. The stochastic version of the functional equation is written as

$$f_n(s_n) = \underset{d_n}{\mathrm{Max}} \left[\sum_{m=1}^{M} P_{nm} [R_n(d_n, s_n, r_{nm}) + f_{n-1}(T_n(d_n, s_n, r_{nm}))] \right] \quad \ldots\ldots\ldots [2]$$

where P_{nm} is the probability that an independent random event, r_{nm}, occurs at stage n and

$$\sum_{m=1}^{M} P_{nm} = 1.0 \qquad (n = 1, 2, \ldots, N)$$

with M being the number of mutually exclusive random events with a common probability distribution at a given stage, n, and N being the total number of stages in a given process.

Although the state variable and the decision variable have been treated as if they were scalars in the previous explanation, they can be multi-dimensional vectors. The sum of the dimensions of the state vector and the decision vector equals the number of degrees of freedom.

The return function at each stage was specified for the purpose of modeling the harvesting process of burley tobacco. Costs or returns were not considered unless they influenced the determination of a decision. For example, the fixed costs for vehicles involved in the system and the costs of family laborers or full-time employees are not included in the return function. It is assumed that decisions are made on a daily basis, and maintained until the next decision point, that is, the next day.

Let $f_n(s_n)$ denote the expected return with n stages remaining and s_n units of land area yet to be harvested following an optimal strategy. Due to the stochastic nature of field workability, the expectation concerning the occurrence of a workable day versus a non-workable day must be quantified. Obviously, there is no expected return for a non-workable day, and the system state remains the same.

The functional equation of the dynamic programming model can now be written to include the consideration of field workability on a work/non-work basis as follows:

$$f_n(s_n) = \underset{[d_n, m_n]}{\mathrm{Max}} \left[P_n [V_n \cdot h \cdot \frac{m_f + m_n}{1 + R} \cdot d_n - C \cdot m_n \cdot d_n + f_{n-1}(s_n - h \cdot \frac{m_f + m_n}{1 + R} \cdot d_n)] + (1 - P_n) f_{n-1}(s_n) \right] \quad \ldots\ldots\ldots [3]$$

TABLE 1. NUMBER OF DAYS AFTER TOPPING AND CORRESPONDING VALUE FACTOR

Days after topping	Value factor	Days after topping	Value factor
7	0.772*	26	0.990
8	0.784	27	0.979
9	0.796	28	0.969
10	0.808	29	0.959
11	0.820	30	0.948
12	0.832	31	0.938*
13	0.844*	32	0.927
14	0.856	33	0.917
15	0.867	34	0.906
16	0.879	35	0.895
17	0.891	36	0.885
18	0.902	37	0.874*
19	0.914	38	0.859
20	0.928	39	0.845
21	0.943	40	0.830
22	0.957	41	0.815
23	0.971	42	0.801
24	0.986	43	0.786*
25	1.000*		

*Given by the experiments conducted by Heggestad and Bowman (1953).

$$(0 \leqslant d_n \leqslant \bar{d}_n,\ m_n = 0,1 \ldots, m_m),$$

$$\bar{d}_n = \text{Min}\left[\frac{s_n(1+R)}{h(m_f+m_n)},\ d_m\right] \qquad \ldots\ldots\ldots\ldots\ldots [4]$$

$$(n \geqslant 2),$$

$$f_1(s_1) = \underset{[d_1, m_1]}{\text{Max}} \left[P_1 (V_1 \cdot h \cdot \frac{m_f + m_1}{1+R} \cdot d_1 - C \cdot m_1 \cdot d_1) \right] \ldots . [5]$$

$$(0 \leqslant d_1 \leqslant \bar{d}_1,\ m_1 = 0,1, \ldots, m_m),$$

$$\bar{d}_1 = \text{Min}\left[\frac{s_1(1+R)}{h(m_f+m_1)},\ d_m\right], \qquad \ldots\ldots\ldots\ldots\ldots [6]$$

where

s_n	=	number of crop land units yet to be harvested at stage n	(ha)
d_n	=	number of hours of harvesting per day at stage n	(hr/day)
d_m	=	maximum number of hours of harvesting per day	(hr/day)
m_f	=	number of family or full-time workers	(man)
m_n	=	number of hired workers at stage n	(man)
m_m	=	maximum number of available hired workers	(man)
h	=	harvesting rate	(ha/man-hr)
C	=	wage rate	($/man-hr)
V_n	=	value of tobacco harvested at stage n	($/ha)
P_n	=	work-day probability at stage n	
R	=	crew assignment index, which is defined later.	

Once the decision process is formulated in terms of a dynamic programming recurrence relation, starting with equation [5], the sequential computations can be made using the results of the preceding computation. The optimal values for decision variables corresponding to a number of equally-spaced values of s_n are searched at each stage. A solution of the dynamic programming model (strategy) thus provides those values of the decision variables, d_n and m_n, which correspond to maximum expected crop return at each stage and for various levels of unharvested crop during the harvesting process. Although the mathematical model presented here is intended to analyze the conventional hand-harvesting system, this model is applicable to a system which involves a mechanical harvester with slight modification.

EVALUATION OF PARAMETERS

Value Factor

The variation in the value of burley tobacco with time after topping depicted in Fig. 1 was experimentally described by Heggestad and Bowman (1953). By harvesting at six-day intervals beginning one week after topping, they determined that the value per unit of crop land area increased significantly due to improvement in both yield and quality during the 18-day period between the first and fourth or normal harvest, and then there was a marked decrease in value during the next 18-day period between the fourth and seventh or final harvest. The maximum value day was 25 days after topping.

In order to avoid the necessity of consideration of variation in average price of tobacco from year to year, the ratios of values at specific times to the maximum value (which will be called the value factor in this study) are calculated, and shown in Table 1. The average value of burley tobacco for crop year 1975 (KAS, 1976) was multiplied by the value factor to determine the value of tobacco in the field at any time.

Work-Day Probability

Field workability is influenced by rainfall and soil trafficability, which is a function of the soil moisture status of the field. However, a practical prediction technique of field workability on a daily basis for locations in Kentucky has not yet been developed. Thus, the number of days available for field work was determined for weekly intervals from observations recorded in the "Weekly Weather and Crop Bulletin", published by the U.S. Department of Commerce and the U.S. Department of Agriculture. Based on this information, the work-day probability or the probability of favorable conditions for field work (on a particular day for each period during the harvesting season) was computed and summarized for central Kentucky in Table 2. The general trend of the work-day probability indicates that workable days are substantially more probable in mid-August than in mid-September.

Cutting Rate

The process of harvesting burley tobacco presently entails the manual cutting and impalement of five or six plants upon a stick and the subsequent transporting and housing of such sticks in a curing barn. Duncan, et al. (1972) summarized labor requirements and costs for burley tobacco production as guidelines for planning and management of production programs. A range in labor requirement is provided because such variation appears prevalent. The observed hand cutting rates range from 0.023 to 0.034 ha/man-hr.

Morey et al. (1971) suggested that the effect of the stochastic harvesting rate on the computational results

TABLE 2. WORK-DAY PROBABILITIES DURING HARVESTING SEASON OF BURLEY TOBACCO IN KENTUCKY

No.	Date	Period	Probability	No.	Date	Period	Probability
1	Aug 9			33	Sep 10		
2	10			34	11		
3	11			35	12		
4	12	1	$P_1 = 0.808$	36	13	5	$P_5 = 0.672$
5	13			37	14		
6	14			38	15		
7	15			39	16		
8	16			40	17		
9	17			41	18		
10	18			42	19		
11	19			43	20		
12	20	2	$P_2 = 0.861$	44	21	6	$P_6 = 0.634$
13	21			45	22		
14	22			46	23		
15	23			47	24		
16	24			48	25		
17	25			49	26		
18	26			50	27		
19	27			51	28		
20	28	3	$P_3 = 0.807$	52	29	7	$P_7 = 0.655$
21	29			53	30		
22	30			54	Oct 1		
23	31			55	2		
24	Sep 1			56	3		
25	2			57	4		
26	3			58	5		
27	4			59	6		
28	5	4	$P_4 = 0.752$	60	7	8	$P_8 = 0.733$
29	6			61	8		
30	7			62	9		
31	8			63	10		
32	9			64	11		

is minor, and it seems that a model using a deterministic harvesting rate is satisfactory. Thus, an average value of 0.028 ha/man-hr is used in this study.

Crew Assignment Index

A crew assignment index, R, is defined as follows:

$$R = \frac{N_h}{N_f}$$

where

N_f = number of workers who are cutting tobacco, and,

N_h = total number of workers who are loading, transporting and housing tobacco.

There are many combinations of the several types of barns and wagons used in harvesting burley tobacco, and each combination has a particular value of R.

Duncan et al. (1971) proposed new cutting and housing methods and illustrated how certain of these methods might work together in an efficient and functional manner. They showed the labor requirement of each operation involved in the system. Using these data, the crew assignment indices for the various systems were computed and tabulated by Miyake (1977).

Supplemental Labor

The utilization of supplemental labor is contingent upon payment of the prevailing wage rate and the availability of workers at any time, depending on the particular situations which may occur during the harvesting season. Extension agricultural engineers at the University of Kentucky suggested that the wage rate of \$4.00 to \$6.00/hr for hand harvesting of burley tobacco prevailed in Kentucky in 1976.

Despite the relatively high wage rate, a labor shortage still remains one of the greatest problems faced by tobacco growers. Both the maximum number of available hired workers and wage rate are highly peculiar to the individual farmer, and therefore, are treated as input variables by the decision model.

RESULTS AND DISCUSSION

An example problem (A) is analyzed and discussed in order to illustrate the interpretation and use of the information provided by the model. Values of input parameters for this hypothetical problem are compiled in Table 3. Days of the harvesting season previously illustrated in Table 2 are referred to as seasonal days. In this example, all tobacco is assumed or required to: (a) be topped on seasonal day 5, (b) attain maximum expected value on seasonal day 30, and (c) be harvested on or before seasonal day 45.

A sample of the strategic information provided by the model is presented in Table 4. Harvesting strategy which corresponds to a selected number of seasonal days and various arbitrary levels of crop remaining are shown for example problem A. Specifically, for each combination of crop level remaining and seasonal day, the solution provides: (a) the expected value of unharvested

TABLE 3. INPUT DATA FOR THE EXAMPLE PROBLEM A

Total Crop Size	2.43	(ha)
Crop Size Increment	0.20	(ha)
Harvesting Rate, h	0.028	(ha/man-hour)
Maximum Harvesting Hours, d_m	10.00	(hours/day)
Maximum Tobacco Value	6116.6	(dollars/ha)
Number of Family Workers, m_f	2	(man)
Maximum number of Available Hired Workers, m_m	3	(man)
Wage Rate, C	5.0	(dollars/man-hour)
Crew Assignment Index, R	2.45	

TABLE 4. ABBREVIATED OPTIMAL STRATEGY FOR EXAMPLE PROBLEM A

Crop Remaining (ha.)	Seasonal Days 21	22	23	24	25	26	27	28	29	30
2.43	13911.70(1)*	13911.70	13910.30	13896.70	13870.10	13832.10	13779.70	13713.60	13629.80	13488.70
	0.00(2)	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
	0.00(3)	0.00	0.00	0.00	0.00	0.00	0.00	3.00	3.00	3.00
2.02	11699.30	11699.30	11699.30	11697.80	11681.40	11652.20	11609.10	11552.80	11484.40	11381.40
	0.00	0.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.00	3.00
1.62	9456.90	9456.90	9456.90	9456.90	9456.90	9441.80	9409.00	9361.50	9300.90	9224.00
	0.00	0.00	0.00	0.00	10.00	10.00	10.00	10.00	10.00	10.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.00
1.21	7173.10	7173.10	7173.10	7173.10	7173.10	7173.10	7156.20	7137.20	7089.20	7022.10
	0.00	0.00	0.00	0.00	0.00	10.00	10.00	10.00	10.00	10.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00
0.81	4834.40	4834.40	4834.40	4834.40	4834.40	4834.40	4834.40	4834.40	4817.70	4780.30
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	10.00	10.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Current Tobacco Value ($/ha.)	5376.50	5450.00	5517.20	5590.60	5676.30	5768.00	5853.70	5939.20	6030.90	6116.60
Harvest Days Remaining	25	24	23	22	21	20	19	18	17	16

* Strategic information given for each combination of remaining crop level and seasonal days is as follows: (1) expected value of remaining crop, provided optimal strategy is followed ($), (2) hours per day per worker to harvest, and (3) number of workers to hire.

crop remaining if optimal strategy is followed, (b) the number of hours to be worked by the harvesting crew (if weather permits), and, (c) the number of workers to hire. For example, the farmer of example problem A (with 2.43 ha) should begin harvesting on seasonal day 22, because this is the first day when "harvesting hours" is nonzero. It was assumed in the formulation of the model that all permanent or family workers would harvest (or not harvest) as a unit, whereas hired laborers could be added individually as required. Thus, optimal strategy on seasonal day 22 calls for the two permanent workers to harvest for ten hours, thereby reducing the level of crop remaining by approximately 0.17 ha. Then, with 2.26 ha remaining on seasonal day 23, the model output would be consulted for optimal strategy for this combination. The reader will note that in Table 4 the amount of crop remaining decreases in increments of approximately 0.4 ha and optimal strategy is shown for only ten seasonal days. If adequate space was available, Table 4 would show the complete output for example problem A, where crop level remaining decreases to zero in increments of 0.2 ha (from 2.43 ha) and time advanced to seasonal day 45.

As harvesting proceeds, optimal strategy can be followed by moving downward and to the right in Table 4, i.e., as crop remaining decreases and time advances. If, as is the case in the present example, the actual level of crop remaining after a given day of harvesting does not exactly correspond to a level which appears in the solution output, then strategy is determined by consulting the tabulated level which best approximates the actual level. The nature of the dynamic programming solution is such that if any such "round-off" errors causes a departure from truly optimal strategy, subsequent harvesting and hiring instructions will tend to force a return to the optimal condition by either speeding up or slowing down the harvesting process.

The dynamic programming technique permits flexible interpretation of the solution as described above, and also provides some important information about the optimality of decisions. A timeliness cost associated with delaying harvest initiation was determined by computing the difference between expected return on the optimal starting day and expected return on the day harvest actually commences. Fig. 2 shows how the timeliness cost for each level of total crop size varies with seasonal days when the values of the parameters d_m, m_f, m_m, C and R remain fixed. It is observed that a larger crop carries a smaller daily cost per unit of total

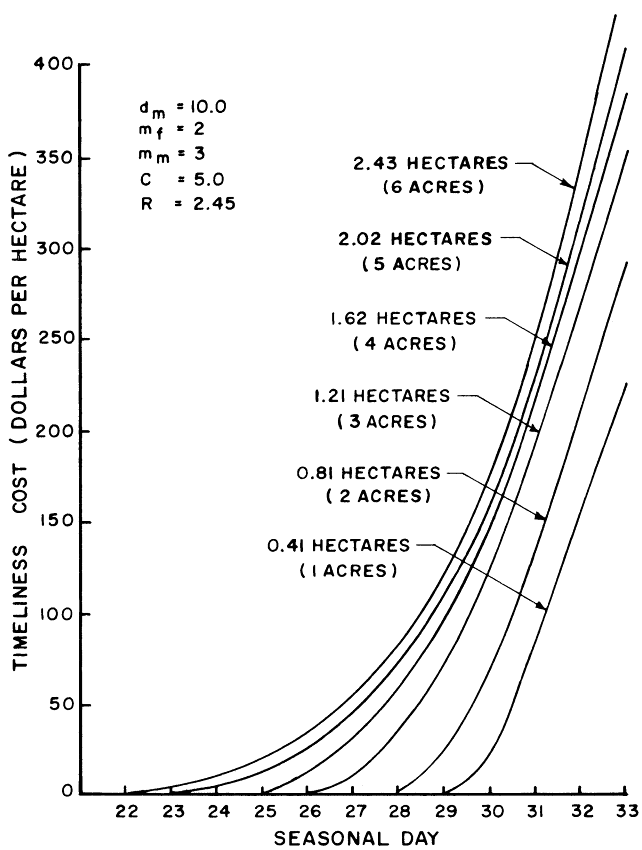

FIG. 2 Variations of timeliness cost with days of delay for various crop levels. (d_m = maximum number of harvesting hours per day, m_f = number of family or full-time workers, m_m = maximum number of available hired workers, C = wage rate (dollars/man-hour), and R = crew assignment index).

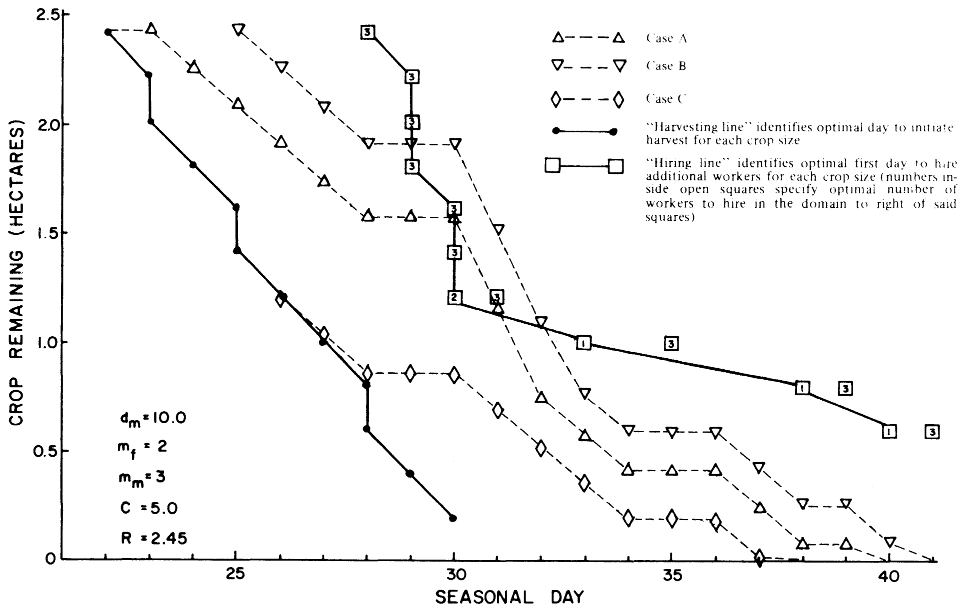

FIG. 3 Three hypothetical harvesting processes under simulated working conditions: Case A - farmer with 2.43 ha crop attempts to follow optimal strategy; Case B - farmer with 2.43 ha crop delays harvest initiation to seasonal day 25; Case C - farmer with 1.41 ha crop attempts to follow optimal strategy. (d_m = maximum number of harvesting hours per day, m_f = number of family or full-time workers, m_m = maximum number of available hired workers, C = wage rate (dollars/man-hour), and R = crew assignment index).

crop area owing to delaying harvest initiation. For example, the optimal starting day for a 2.43 ha crop is seasonal day 22, however, harvest initiation can be delayed for a short time because the timeliness cost is quite small. For a delay of three days, the loss due to the delay is $17.12/ha. However, for the farmer who has a 0.81 ha crop, a delay of three days implies a loss of $147.06/ha. It should be pointed out that the optimum expected return for a larger crop may be increased by increasing d_m, m_f, or m_m. This fact is not considered in the definition of timeliness cost, which must be associated with a particular set of system parameters.

Fig. 3 illustrates three hypothetical harvesting operations which take place under climatic conditions issued for central Kentucky during the tobacco harvesting season of 1975 (WW & CB, 1975). In case A, a farmer with a 2.43 ha (6 acre) crop attempts to follow exactly the optimal strategy given in Table 4 and tries to start harvesting on seasonal day 22; however, harvest initiation is delayed one day because of unfavorable field conditions. In case B, a farmer with a 2.43 ha (6 acre) crop accepts a timeliness cost of $17.12/ha by delaying harvest initiation until seasonal day 25, but, thereafter attempts to follow optimal strategy from Table 4. In case C, a farmer with a 1.21 ha (3 acre) crop initiates harvest on seasonal day 26 (which is the optimal starting day for this crop size) and attempts to follow optimal strategy. With the exception of crop size in case C, input data for these operational conditions are identical to example problem A.

In Fig. 3, the lines representing harvesting operations A, B, and C proceed downward and rightward as remaining crop levels decrease and time advances. The bold unbroken line on the left identifies the optimal day to initiate harvest for each possible crop size. It is hereafter denoted as the "harvesting line" because under optimal strategy no harvesting takes place in the domain to the left of this line. The bold unbroken line on the right identifies the optimal day to first introduce hired labor for each level of unharvested crop remaining. This line is hereafter denoted as the "hiring line" because, under optimal strategy, no supplemental workers are hired in the domain to the left of this line. Harvesting activity in the domain between the harvesting line and the hiring line is necessarily accomplished with a permanent labor force.

The numbers inside the symbols associated with the hiring line indicate the optimal number of workers to hire initially for each level of crop remaining. Numbers inside symbols to the right of the hiring line indicate, for a particular level of crop remaining, how additional workers should be hired as time proceeds.

In case A, three workers are hired on seasonal days 30 and 31 and the remaining harvesting is accomplished by the permanent crew. In case B, three workers are also hired on seasonal days 30 and 31. Note that hiring strategy would have been altered in case B had seasonal day 29 been a suitable day for work. Also note that optimal strategy as illustrated in Fig. 3 indicates that in case A workers should be hired on seasonal day 31, yet does not clearly specify the number to hire. The same uncertainty exists relative to case B on seasonal day 32. In fact, the choice is essentially arbitrary in that, as discussed previously, any departure from optimality is corrected by subsequent strategy. Three workers were hired in the former case and two in the latter. In case C, harvesting is accomplished entirely by the permanent crew.

For each case illustrated in Fig. 3, the return at each stage can be computed using the return function defined in the functional equation [3]. Table 5 shows the details of such computations for each of the three cases. Total returns are very close to the expected total returns for all cases. It is observed that the farmer in case B starts harvesting three days later than the one in case A and completes harvesting only one day later. This is because, by following hiring strategy, he introduces more hired workers than the farmer of case A, aiming at the high value tobacco around seasonal day 30.

TABLE 5. COMPUTATIONS OF RETURNS FOR THREE HYPOTHETICAL HARVESTING PROCESSES

		Case A (13912)*			Case B (13870)*			Case C (7173)*		
†	‡	Crop remaining‖	Return	§	Crop remaining‖	Return	§	Crop remaining‖	Return	§
22	N	2.43	0	0	2.43		0	1.21	0	
23	W	2.26	906.52	0	2.43		0	1.21	0	0
24	W	2.10	918.58	0	2.43		0	1.21	0	0
25	W	1.93	932.66	0	2.26	932.66	0	1.21	0	0
26	W	1.77	947.73	0	2.10	947.73	0	1.05	947.73	0
27	W	1.61	961.81	0	1.93	961.81	0	0.87	961.81	0
28	N	1.61	0	0	1.93	0	0	0.87	0	0
29	N	1.61	0	0	1.93	0	0	0.87	0	0
30	W	1.20	2362.53	3	1.53	2362.53	3	0.72	1005.01	0
31	W	0.79	2337.36	3	1.12	2337.36	3	0.56	994.94	0
32	W	0.62	983.90	0	0.79	1867.80	2	0.39	983.90	0
33	W	0.46	973.87	0	0.62	973.87	0	0.23	973.87	0
34	N	0.46	0	0	0.62	0	0	0.23	0	0
35	N	0.46	0	0	0.62	0	0	0.23	0	0
36	W	0.29	942.69	0	0.46	942.69	0	0.06	942.69	0
37	W	0.13	931.65	0	0.29	931.65	0	0	362.56	0
38	N	0.13		0	0.29	0	0	0	0	0
39	W	0	708.69	0	0.13	910.54	0	0	0	0
40	W	0		0	0	700.10	0	0	0	0
		Total	13907.99	6	Total	13868.74	8	Total	7172.52	0

*Expected total return.
†Seasonal day.
‡W implies workday, and N implies non-workday.
§Number of hired workers.
‖Crop remaining at the end of the day (hectares).

Fig. 4 shows strategies for three systems with different maximum numbers of available hired workers. It is observed that when $m_m = 3$ and $m_m = 5$, the introduction of hired workers is made by steps. Although there are some variations, these three systems have very similar strategies, with the harvesting lines differing only with 2.43 ha remaining. The same trends were approximately observed regardless of the maximum number of available hired workers.

Fig. 5 shows the effects of changes in wage rate upon strategy. An increase in wage rate has little effect on the harvesting line except to initiate harvesting somewhat earlier for relatively large crops. As expected, an increase in wage rate tends to delay the hiring of additional workers for nearly all levels of crop remaining.

Because timeliness losses are closely related to the possibility of introducing the hired workers, timeliness costs which correspond to the systems with a wage rate of $8.00/man-hr increase more rapidly than timeliness costs of systems with a wage rate of $5.00/man-hr as shown in Fig. 6. The effects of the changes in wage rate on timeliness costs are smaller in relatively small crops.

Increasing the maximum harvesting hours per day has the same effect as increasing the processing capacity of a system and vice versa. Therefore, an increase in the maximum harvesting hours has the same type of effect on harvesting strategy as an increase in the number of family workers, or an increase in the harvesting rate, etc. Thus, the effects of the maximum harvesting hours are discussed in terms of the processing capacity of a harvesting system.

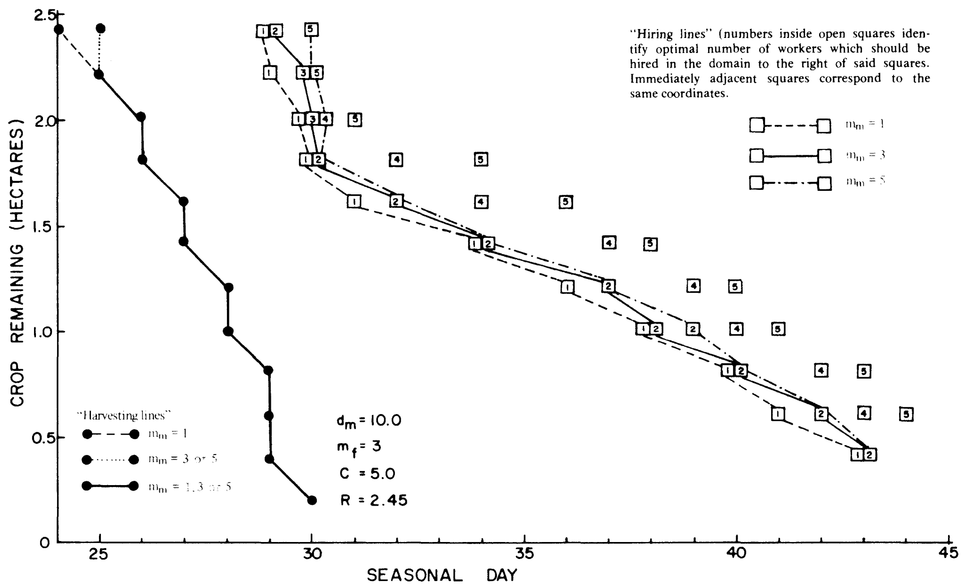

FIG. 4 Effect of maximum available hired workers on strategy. (d_m = maximum number of harvesting hours per day, m_f = number of family or full-time workers, m_m = maximum number of available hired workers, C = wage rate (dollars/man-hour), and R = crew assignment index).

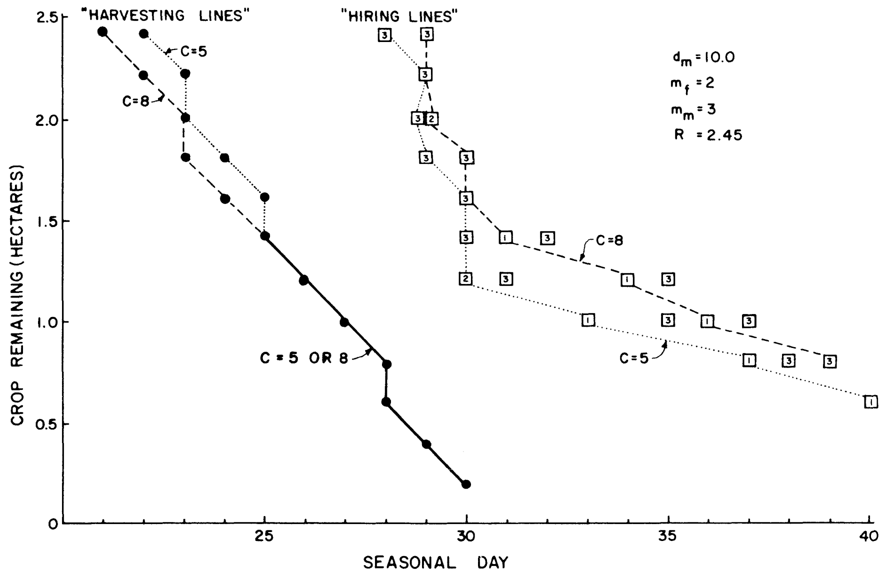

FIG. 5 Effect of wage rate on strategy. (d_m = maximum number of harvesting hours per day, m_f = number of family or full-time workers, m_m = number of available hired workers, C = wage rate (dollars/man-hour), and R = crew assignment index).

An increase in the processing capacity of a system causes the initial harvest to take place later, as shown in Fig. 7. On the other hand, an increase in the processing capacity of a system entails changes in timeliness cost. In Fig. 8, it is observed that a larger processing capacity causes a higher rate of increase in timeliness cost, and the extent of the effects of processing capacity on timeliness cost is smaller in relatively small crops.

SUMMARY

The decision-making process associated with the scheduling of burley tobacco harvesting operations was formulated as a multi-stage decision process and solved using dynamic programming. The solution of a stochastic dynamic programming model provides a set of optimal decision rules, that is, a strategy. When certain user-specified parameters are provided, the decision model provides information concerning the optimal date to start harvesting, the optimal number of hours to harvest on each day, the optimal date to introduce hired labor and the optimal number of workers which should be hired.

The solution of the dynamic programming model makes it possible to compute a timeliness coefficient which is defined as the amount of the expected total return which is lost because of delaying harvest initiation beyond the optimal starting day. Thus a decision-maker can consult the solution table in any situation during the harvesting season and make decisions with the aid of the timeliness coefficient.

Further development of the decision model may include collective management of several tobacco fields with different topping dates, treatment of system parameters as stochastic variables, and adaptive revision of probabilities associated with stochastic events over time.

References

1 Bellman, R. E. 1957. Dynamic programming. Princeton University Press, Princeton, NJ.

2 Bellman, R. E. and S. E. Dreyfus. 1962. Applied dynamic programming. Princeton University Press, Princeton, NJ.

3 Duncan, G. A., W. W. Hourigan and J. H. Smiley. 1972. Burley tobacco production costs. Leaflet No. 344, Cooperative Extension Service, University of Kentucky, Lexington,

4 Duncan, C. A., J. H. Casada, E. E. Yoder and W. H. Henson, Jr. 1971. Burley mechanization. Miscellaneous bulletin No. 393. Cooperative Extension Service, University of Kentucky, Lexington.

5 Heggestad, H. E. and D. R. Bowman. 1953. Burley tobacco

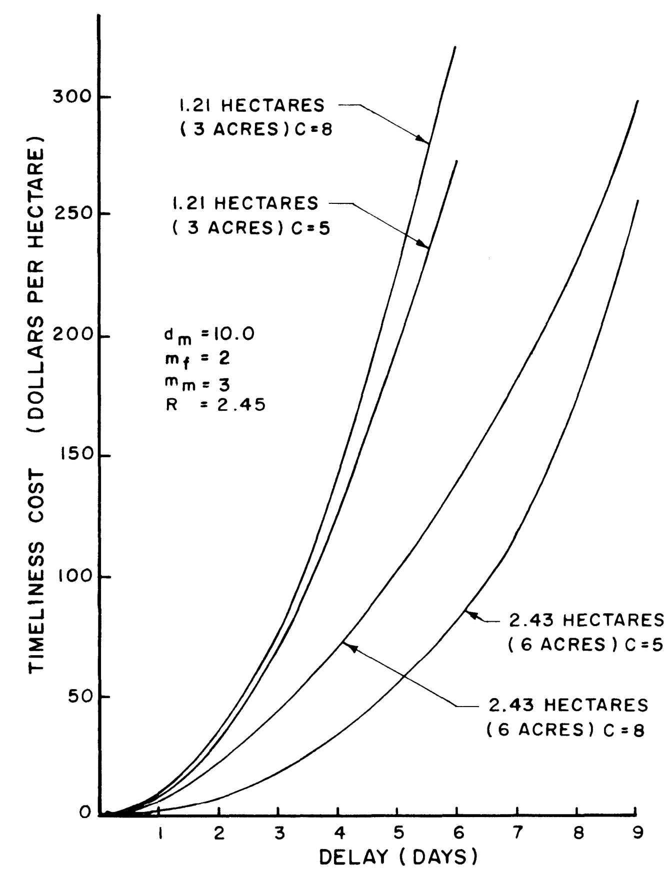

FIG. 6 Variation of timeliness cost with days of delay for different crop levels and wage rates. (d_m = maximum number of harvesting hours per day, m_f = number of family or full-time workers, m_m = maximum number of available hired workers, c = wage rate (dollars/man-hour), and R = crew assignment index).

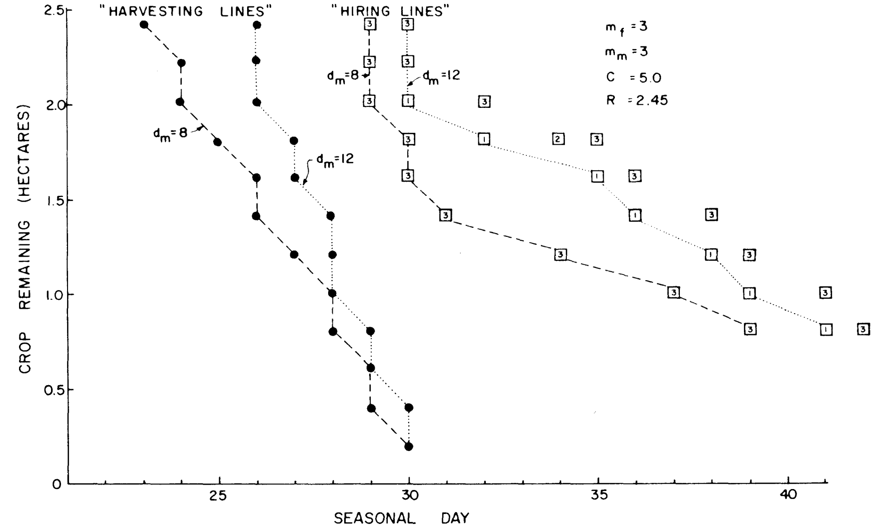

FIG. 7 Effect of maximum harvesting hours on strategy. (d_m = maximum number of harvesting hours per day, m_f = number of family or full-time workers, m_m = maximum number of available hired workers, C = wage rate (dollars/man-hour), and R = crew assignment index).

quality, yield and chemical composition as affected by time of harvest. Bulletin No. 230, Agricultural Experiment Station, University of Tennessee, Knoxville.

6 Jenkins, K. G. and A. N. Halter. 1963. A multi-stage stochastic replacement decision model. Agricultural Experiment Station Technical Bulletin No. 67, Oregon State University, Corvallis.

7 Kentucky Agricultural Statistics. 1962-1976. Kentucky Crop and Livestock Reporting Service, Statistical Reporting Service, U.S. Department of Agriculture and Ky. Department of Agriculture, Louisville, KY.

8 Liang, T. 1969. Optimal agricultural product size sorting operation by dynamic programming method. Journ. of Agric. Engineering Research 14(2):139-146.

9 Liang, T. and D. A. Link. 1970. Farm machinery maintenance. TRANSACTIONS of the ASAE 13(3):395-405.

10 Low, E. M. and J. K. Brookhouse. 1965. Dynamic programming and the selection of replacement policies in commercial egg production. Journ. of Agric. Economics 18(3):339-350.

11 Miyake, Yasuhiko. 1977. Determination of strategy for harvesting burley tobacco using dynamic programming. Unpublished M.S. thesis, University of Kentucky, Lexington.

12 Morey, R. V., G. L. Zachariah and R. M. Peart. 1971. Optimum policies for corn harvesting. TRANSACTIONS of the ASAE 14(5):787-792.

13 Schroeder, M. E. and R. M. Peart. 1967. Dynamic programming method of air allocation in a grain drier. TRANSACTIONS of the ASAE 10(1):96-99.

14 Weekly weather and crop bulletin. 1970-1975. U.S. Dept. of Commerce, National Oceanic and Atmospheric Admin. and U.S. Dept. of Agric., Statistical Reporting Service, Washington, DC.

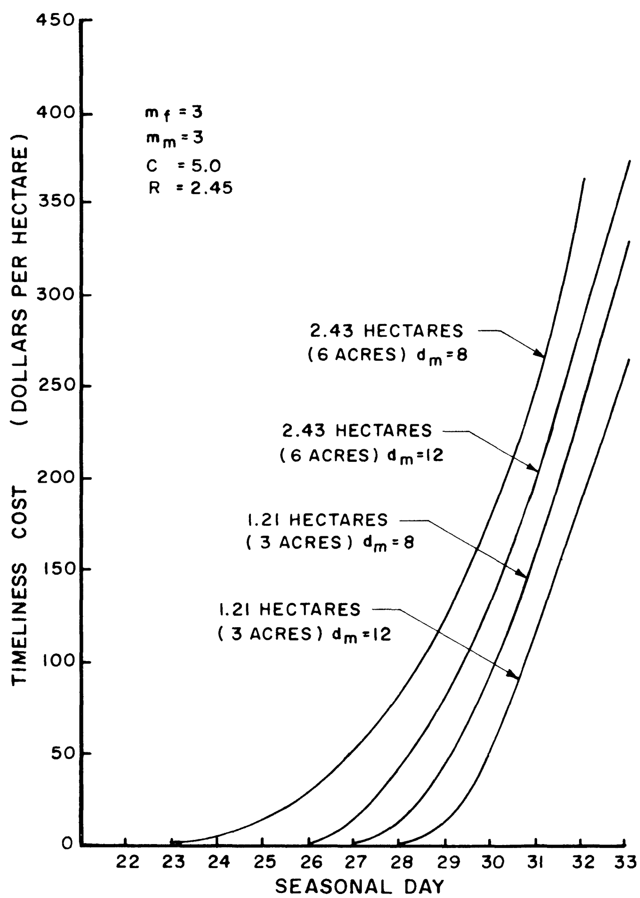

FIG. 8 Variation of timeliness cost with seasonal day for different crop levels and maximum harvesting hours. (d_m = maximum number of harvesting hours per day, m_f = number of family or full-time workers, m_m = maximum number of available hired workers, C = wage rate (dollars/man-hour), and R = crew assignment index).